

# HYBOX

(version 1.1)

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The forerunner of the program HYBOX dates back to the early 1980s, at which time it represented an important stepping stone on the path to full-fledged isopycnic general circulation modeling. It featured a 32 x 32 point rectangular basin, 4 isopycnic layers, longitude-dependent bottom depth, and latitude-dependent wind forcing. The most innovative aspect of the model was the use of the new Flux Corrected Transport algorithm in the solution of the continuity equation. This algorithm allowed isopycnic model layers to "dry up", i.e., outcrop at the sea surface, thereby exposing denser layers to the atmosphere – a crude attempt (crude at low vertical resolution) to emulate surface density contrasts.

Today, HYBOX, due to its relative simplicity, serves as a hybrid-isopycnic "toy" model. It allows users to experiment with the **hybrid-isopycnic coordinate layout** – specifically, with prescriptions for minimum layer thickness and the choice of "target" values for layer density, both of which affect the vertical spacing of layer interfaces in different parts of the ocean basin. The need for such experimentation is apparent, given the lack of familiarity of some HYCOM users with the role and significance of parameters that are special to layered ocean models.

To keep the model simple, buoyancy forcing has been added to the original wind-forced model in a rather crude fashion. (This simplicity undoubtedly affects the realism of the simulated circulation.) A traditional bulk formula is used to infer buoyancy fluxes at the sea surface from the difference between a prescribed, annually varying, latitude-dependent air temperature and a sea surface temperature derived from surface density under the assumption of constant salinity. The buoyancy flux is assumed to vary linearly with depth and reaches zero at a "mixed layer depth" which is a simple exponential function of buoyancy flux. Note that the hybrid coordinate framework allows the buoyancy flux to directly modify density in layers falling within the mixed layer depth range – a capability not present in purely isopycnic models where buoyancy forcing must first be translated into interface displacements.

The formula for mixed layer depth has been tuned to yield depths of  $\sim 30$  m in case of strong surface warming, and of 1000 m or more in case of very strong cooling. Additional vertical mixing of density takes place through a convective adjustment mechanism triggered by the onset of static instability.

Wind stress is a prescribed function of latitude and is distributed among near-surface layers by assuming a linear stress profile reaching zero at a depth of *wstres*. As presently written, the wind stress pattern is a conventional extratropical double-gyre pattern, cyclonic at high and anticyclonic at low latitudes.

A linearly varying stress profile, reaching zero at height *bstres* above the sea floor, is also used for bottom stress which is set proportional to the velocity in the lowest model layer. Top and bottom stresses are distributed among all those layers that fall within the depth ranges *wstres* and *bstres*, respectively.

Strength of wind and buoyancy forcing is regulated by two parameters, (a) the maximum wind stress *taumax* and (b) a reference surface wind speed *airsea*. While these two parameters are related in the real world, they are treated here as independent parameters.

Starting from rest with flat layer interfaces, the model solves nonlinear conservation equations for momentum, mass, and density (thermal energy). Omitting vertical advection as well as lateral mixing, vertical

stress, and external forcing to highlight the primary dynamical terms, the equations assume the form

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla \frac{\mathbf{v}^2}{2} + (\zeta + f) \mathbf{k} \times \mathbf{v} = -\nabla M \quad (1)$$

$$\frac{\partial \Delta p}{\partial t} + \nabla \cdot (\mathbf{v} \Delta p) = 0 \quad (2)$$

$$\frac{\partial(\rho \Delta p)}{\partial t} + \nabla \cdot [\mathbf{v}(\rho \Delta p)] = 0 \quad (3)$$

where  $\Delta p$  is layer thickness (actually, layer mass per unit area) and  $M$  is the Montgomery potential  $gz + p/\rho$  satisfying the hydrostatic equation

$$\frac{\partial M}{\partial \rho} = -\frac{p}{\rho^2}. \quad (4)$$

All other variables have their conventional meaning. Fast-moving barotropic gravity waves are eliminated by removing the divergent component from the barotropic velocity field. This filtering device, analogous to a rigid lid in  $z$  coordinates, allows a 20- to 30-fold lengthening of the time step. The continuity equation (2) is solved using the FCT algorithm which allows layers to collapse to zero thickness. Velocity values computed at massless grid points are discarded and replaced by values from a non-massless layer above or below.

A vertical "grid generator" oversees the spacing of layer interfaces. Its actions are governed by the (often conflicting) mandates to maintain minimum layer thickness and the isopycnic character of model layers. Specifically, the job of the grid generator is to divide the material vertical motion  $dp/dt$ , which is obtained at every grid point and every time step by solving a vertically integrated form of (2), into two components: vertical motion of layer interfaces and vertical motion relative to them. In equation form:

$$\begin{pmatrix} \text{vertical} \\ \text{motion} \\ \text{of layer} \\ \text{interface} \end{pmatrix} + \begin{pmatrix} \text{vertical} \\ \text{motion} \\ \text{through} \\ \text{interface} \end{pmatrix} = \begin{pmatrix} \text{vertically} \\ \text{integrated} \\ \text{horizontal} \\ \text{mass-flux} \\ \text{divergence} \end{pmatrix}. \quad (5)$$

The second term on the left represents the generalized vertical velocity which is needed to evaluate vertical advection terms (not explicitly stated in the conservation equations (1) - (3)).

Density, momentum, and layer interface depth are diffused horizontally, using a constant eddy diffusivity which in the case of momentum mixing is enhanced by a deformation-dependent component. Diffusion of isopycnic interface depth is known as Gent-McWilliams eddy parameterization.

Parameters that are prime candidates for experimentation are read in via a *namelist*. Parameters less likely to be changed (grid dimensions, mesh size, time step, beta, mixing parameters, ....) are defined in a module named *control*; their change requires recompilation of the code.

The items in *namelist* are

- *airsea* – wind speed used in bulk formula for air-sea fluxes
- *taumax* – maximum east-west wind stress
- *ndays* – number of days for the model to run.
- *restart* – logical variable; if *true*, model restarts from a previously generated restart file.
- *tnor\_win*, *tnor\_sum* – air temperature ( $^{\circ}\text{C}$ ) at the northern edge of the basin in winter/summer.
- *tsou\_win*, *tsou\_sum* – air temperature ( $^{\circ}\text{C}$ ) at the southern edge of the basin in winter/summer.

- *target* – "target" potential density ( $\text{kg m}^{-3}$ –1000) of each model layer.
- *thini* – initial potential density ( $\text{kg m}^{-3}$ –1000) of each model layer.
- *dpini* – initial thickness (m) of each model layer.
- *thkmn* – minimum thickness (m) of each model layer.
- *ale* – logical variable; if *true*, the ALE algorithm is invoked to maintain a hybrid-isopycnic grid; if *false*, the vertical grid remains fixed (i.e., Cartesian).

A special code block in hybox.F uses NCAR graphics commands to output model results in graphical form. This output option is activated by the `#ifdef NCARG` preprocessor directive in the *makefile* supplied with the HYBOX source code. Rudimentary contour plots of some scalar fields, as well as vertical sections showing interface depth at different longitudes and times, are generated in *stdout* for users not having access to NCAR graphics. To simplify the line-by-line output logic, the cross sections in *stdout* are turned  $90^\circ$  to the left, i.e., the left edge of the printout represents the sea surface and depth increases to the right. Contour plots are emulated in *stdout* by "zebra" striping, using the digits 0 – 9 alternating with blanks. A contour line whose value is  $N$  times the stated contour interval is represented in the zebra plot by the digit  $\text{mod}(N, 10)$ .

Users intending to modify the source code should be aware of the following conventions:

1. Grid points are numbered like matrix elements, with point (1,1) located in the upper left (northwest) corner. The coordinate system is right-handed but oriented such that the  $x$  axis points down (south), i.e., in the direction of increasing row index  $i$ , while the  $y$  axis points to the right (east), in the direction of increasing column index  $j$ .
2. Arakawa C grid staggering is used. Velocity array elements  $u(i, j)$  and  $v(i, j)$  are actually located at geographic location  $(i - \frac{1}{2}, j)$  and  $(i, j - \frac{1}{2})$ , respectively, relative to mass point  $i, j$ . The same holds for the horizontal mass flux components.
3. The leap frog time difference scheme requires two time slots for each prognostic variable. Since early versions of Fortran did not permit more than 3 array dimensions, space for the two time slots in the prognostic variable arrays is provided by doubling the size of the vertical dimension  $kdm$ . Variables  $m$  and  $n$ , which alternate between the values 1 and 2, are used to denote the "mid time" and "old/new" time slot, respectively. Data in time slots  $m$  and  $n$  start at  $k = 1 + mm$  and  $k = 1 + nn$ , respectively, where  $mm = (m - 1)kdm$  and  $nn = (n - 1)kdm$ .
4. The FFT solver used for the rigid lid requires a north-south grid dimension of  $idm = 2^{nat'l number} + 1$ .

OpenMP directives are supplied in the Fortran source code to facilitate parallel execution on shared-memory platforms.

## Sample Results

As already mentioned, the main purpose of HYBOX is to demonstrate the multitude of vertical grids that result from different specifications of minimum layer thickness and target density.

Results shown below were obtained on a  $64 \times 64 \times 5$  grid ( $idm = jdm = 65$ ,  $kdm = 5$ ) with a 50 km mesh size and a time step of 36 min (40 steps per day). In all experiments, target densities, initial layer thicknesses, air temperature and run time were set, respectively, to

```
! --- target potential densities (sigma_theta units):
target(1)      = 24.6
target(2)      = 25.7
target(3)      = 26.4
target(4)      = 26.8
target(5)      = 27.0
! --- initial layer thickness (m):
dpini(1)       = 100.
dpini(2)       = 300.
dpini(3)       = 600.
dpini(4)       = 1000.
dpini(5)       = 3000.
! --- air temperature at northern/southern basin edge:
tnor_win = -30.
tnor_sum = 5.
tsou_win = 35.
tsou_sum = 35.
ndays    = 1800          ! number of days to run (1 year = 360 days)
```

**Experiment 1:** Strong wind forcing, no thermal forcing, small minimum layer thickness values.

```
! --- minimum layer thickness (m):
thkmn(1)       = 30.
thkmn(2)       = 30.
thkmn(3)       = 30.
thkmn(4)       = 30.
thkmn(5)       = 30.
! --- forcing choices:
airsea = 0.          ! surface wind speed (m/s); zero -> no thermal forcing
taumax = 0.2         ! max. wind stress (N/m^2); zero -> no wind forcing
```

The fields resulting from this particular setup are shown in Fig.1 and represent a classical wind-forced double gyre pattern. The strong recirculation cells near the western boundary are an artifact resulting from low viscosity values not adhering to Munk layer scaling. The surface density field and the cross sections indicate that layer 2 water is pulled to the surface in the cyclonic northern gyre, invading layer 1 which maintains its assigned nonzero minimum thickness.

**Experiment 2:** Weak wind, strong buoyancy forcing, larger minimum layer thickness.

```
! --- minimum layer thickness (m):
thkmn(1)       = 75.
thkmn(2)       = 125.
thkmn(3)       = 175.
```

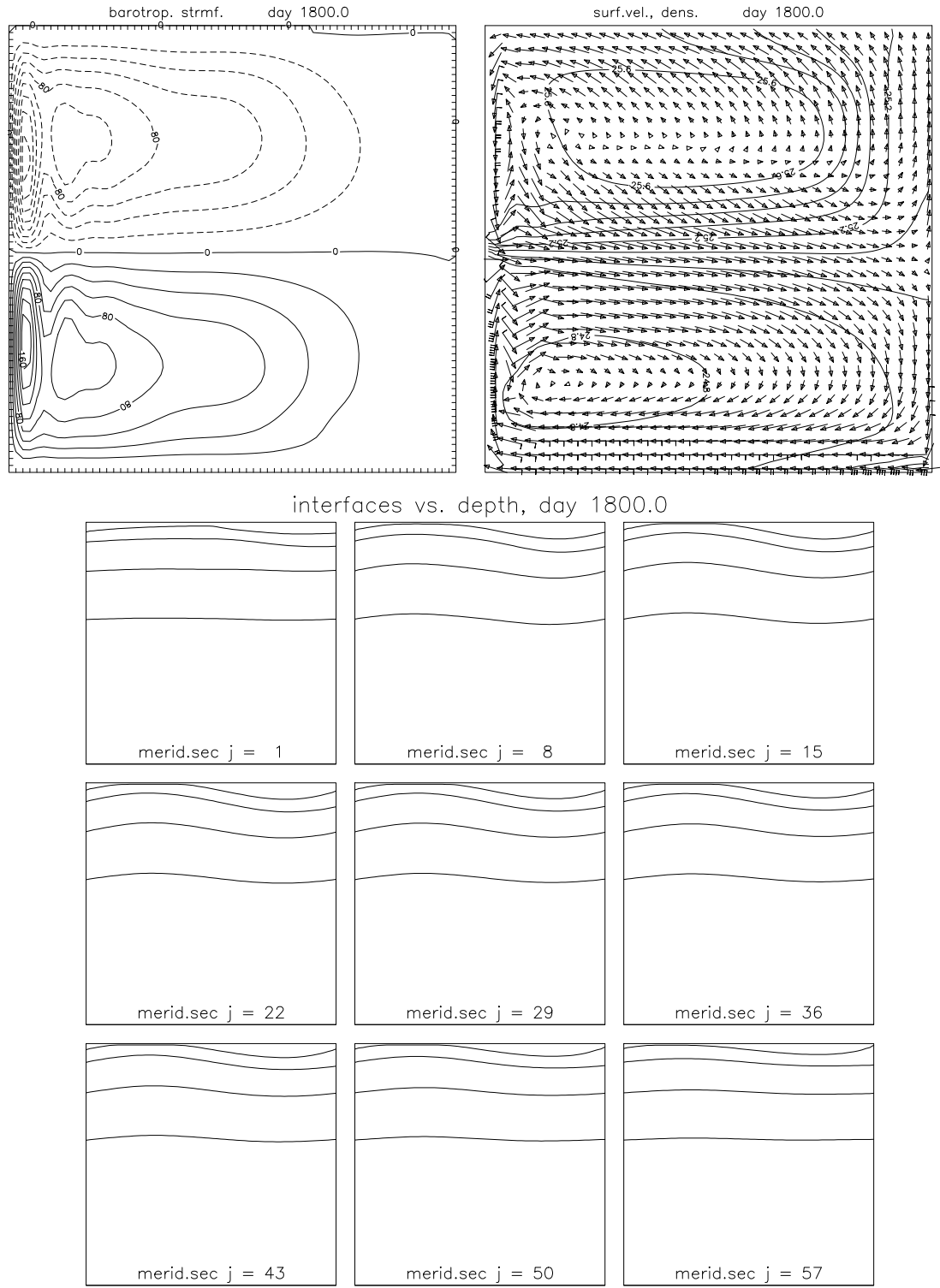


Figure 1: Results from experiment 1 at year 5.0. Upper left: barotropic stream function. Upper right: surface velocity vectors and surface density. Bottom: vertical sections through model domain along 9 equally spaced meridians progressing west to east(north to the left).

```

thkmn(4)      = 225.
thkmn(5)      = 275.
! --- forcing choices:
airsea  = 10.      ! surface wind speed (m/s); zero -> no thermal forcing
taumax  = 0.1      ! max. wind stress (N/m^2); zero -> no wind forcing

```

The stream function contour plot is dominated in this case by a pair of intense eddies in the northwestern quadrant of the southern anticyclonic gyre (Fig. 2). While a southern gyre circulation is still visible in the surface flow, the surface signature of the wind-forced northern gyre has been obliterated. Instead, we see eastward flow throughout the northern gyre domain, strongest along a surface density front near the northern basin edge.

Strong wintertime surface cooling has led at year 5 to outcropping of layer-2 and layer-3 water near the northern basin edge. Both layers 1 and 2 have therefore changed into constant-depth layers in that region. Wintertime density forcing appears to primarily create layer-3 mode water. Downwelling in the southern gyre has led to substantial tightening of the thermocline.

Due to the long adjustment time of buoyancy-forced circulations, the fields in Fig. 2 show a transitional state far from equilibrium.

### **Experiment 3:** Target densities too high for the problem at hand.

This condition is achieved by filling the basin with relatively light water initially, causing interfaces to descend to the bottom.

```

! --- initial densities (sigma_theta units):
thini(1)      = 22.6
thini(2)      = 23.7
thini(3)      = 24.4
thini(4)      = 24.8
thini(5)      = 25.0
! --- minimum layer thickness (m):
thkmn(1)      = 75.
thkmn(2)      = 125.
thkmn(3)      = 175.
thkmn(4)      = 225.
thkmn(5)      = 275.
! --- forcing choices:
airsea  = 2.      ! surface wind speed (m/s); zero -> no thermal forcing
taumax  = 0.2      ! max. wind stress (N/m^2); zero -> no wind forcing

```

Relatively weak thermal forcing allows the wind-forced gyre circulation to dominate the barotropic stream function plot in this case (Fig. 3). Due to the mismatch between water density and target isopycnals, 3 of the 4 layer interfaces have migrated to the sea floor. Vertical separation of those interfaces is achieved for display purposes by the introduction of a 50 m minimum layer thickness *thkbot* in layers that normally would be reduced to zero thickness at the bottom<sup>1</sup>.

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<sup>1</sup>Over steep bottom slopes, maintaining a nonzero minimum thickness of near-bottom layers by setting *thkbot* > 0 is **not** recommended in HYCOM as this will create pressure gradient errors familiar from sigma coordinate models.

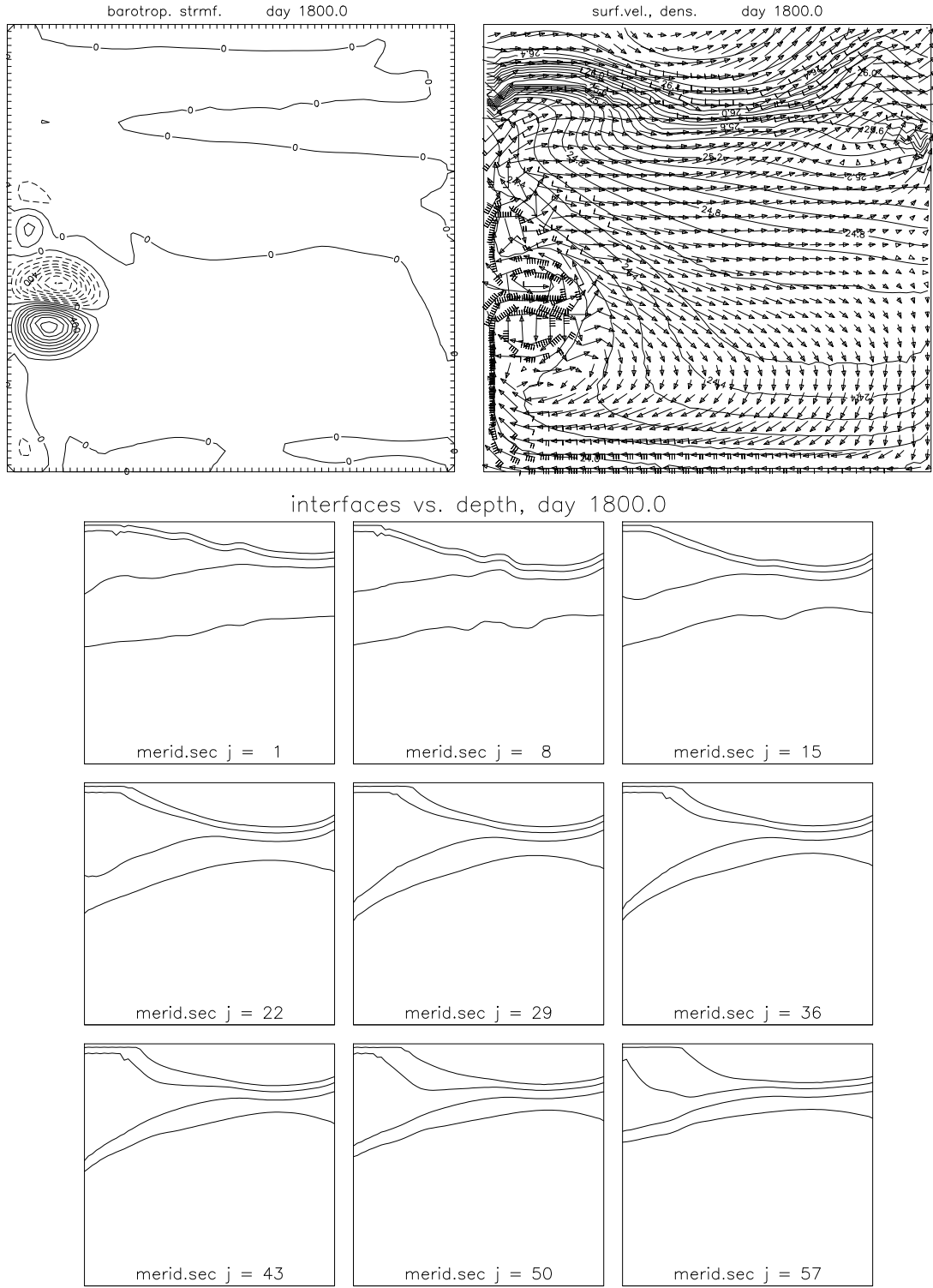


Figure 2: Results from experiment 2 at year 5.0. Upper left: barotropic stream function. Upper right: surface velocity vectors and surface density. Bottom: vertical sections through model domain along 9 equally spaced meridians progressing west to east.

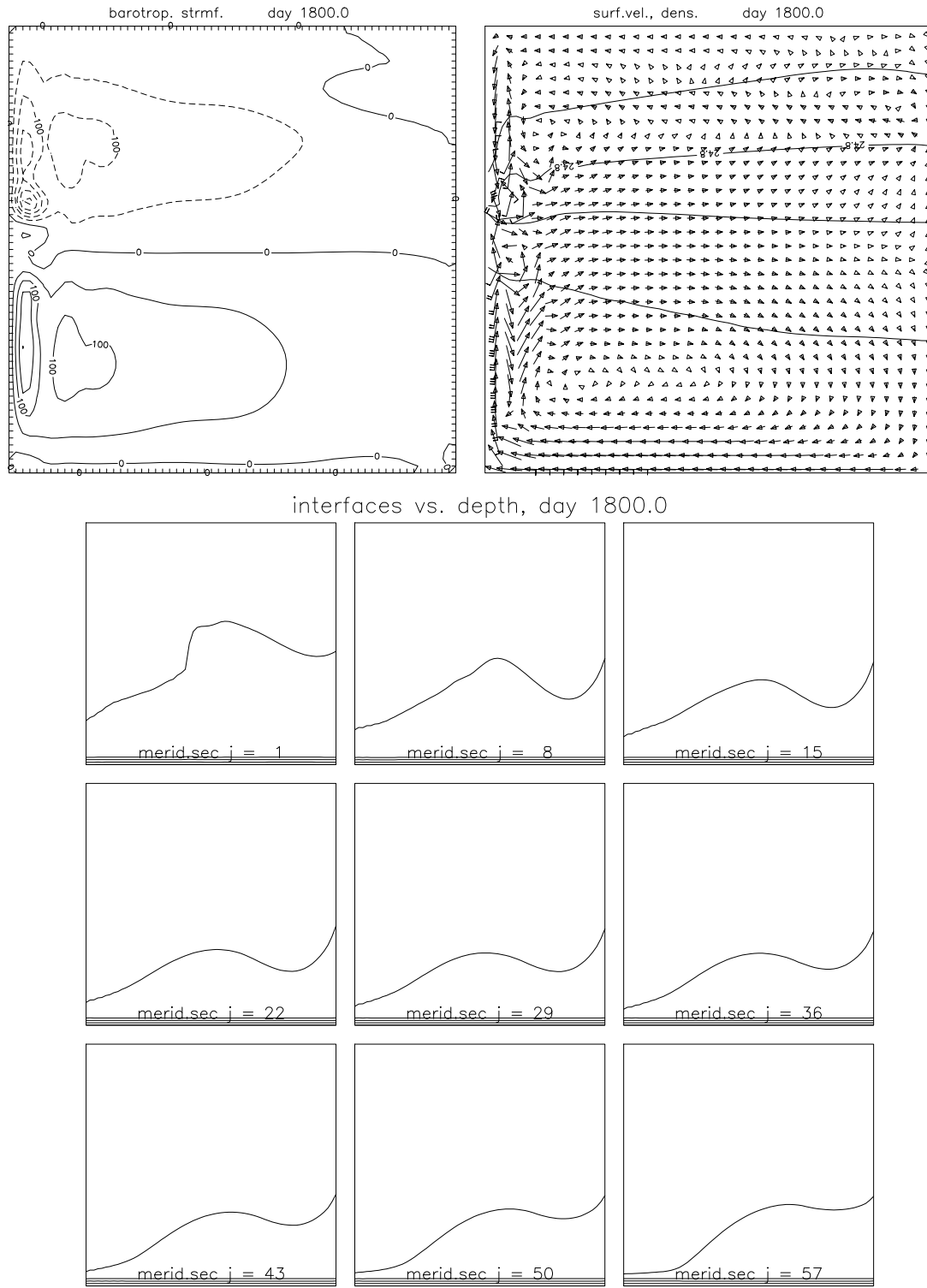


Figure 3: Results from experiment 3 at year 5.0. Upper left: barotropic stream function. Upper right: surface velocity vectors and surface density. Bottom: vertical sections through model domain along 9 equally spaced meridians progressing west to east.

#### **Experiment 4:** Target densities too low for the problem at hand.

This condition is achieved by filling the basin with relatively dense water initially, causing interfaces to rise to the top.

```
! --- initial densities (sigma_theta units):
thini(1)      = 25.6
thini(2)      = 26.7
thini(3)      = 27.4
thini(4)      = 27.8
thini(5)      = 28.0
! --- minimum layer thickness (m):
thkmn(1)      = 75.
thkmn(2)      = 125.
thkmn(3)      = 175.
thkmn(4)      = 225.
thkmn(5)      = 275.
! --- forcing choices:
airsea = 2.          ! surface wind speed (m/s); zero -> no thermal forcing
taumax = 0.2         ! max. wind stress (N/m^2); zero -> no wind forcing
```

The situation depicted here may occur if target densities suitable for low-latitude models are used in limited-area models of the Arctic Ocean. HYBOX responds to the mismatch by converting all layers to shallow constant-depth layers crowding the upper portion of the water column. This severely degrades vertical grid resolution in the deeper ocean.

Using unrealistically light target values is a legitimate strategy, however, for providing a "guaranteed" number of fixed-depth layers near the surface for evaluating air-sea fluxes or using  $z$ -coordinate based turbulence closure schemes. To obtain reasonable grid point spacing in this case, much larger minimum layer thicknesses than used here may be required (see next experiment).

The localized density maxima in the southern portion of the domain seen in the surface density plot, also visible in the  $j=29$  cross section, are quasi-permanent features. They may reflect a yet-to-be-understood feedback mechanism in the simplified thermal forcing scheme.

#### **Experiment 5:** Sigma coordinate representation on coastal shelf.

The grid generator can easily be modified to change the character of constant-depth layers to sigma layers anywhere in the domain (sigma = depth scaled by bottom depth). Due to the fact that the rigid lid algorithm in HYBOX allows bottom depth to vary in  $j$  (east-west) direction, we can demonstrate the sigma coordinate feature by adding a shelf sea extending from the southern to the northern boundary.

The cross sections in Fig. 5, which in this particular case are running in east-west direction (i.e., at constant  $i$ ), show a coordinate layout obtained by multiplying  $thkmn(k)$  at each grid location  $i, j$  by the factor

$$\min \left( 1, \frac{z_{bot}(i, j)}{1000 m} \right)$$

where  $z_{bot}$  is the bottom depth. The denominator in this formula should be of the same general magnitude as the depth of the shelf edge; its role is to prevent interfaces that intersect the sea floor at depths *below* the shelf edge from climbing up onto the shelf because this might create sigma-coordinate type pressure gradient problems.

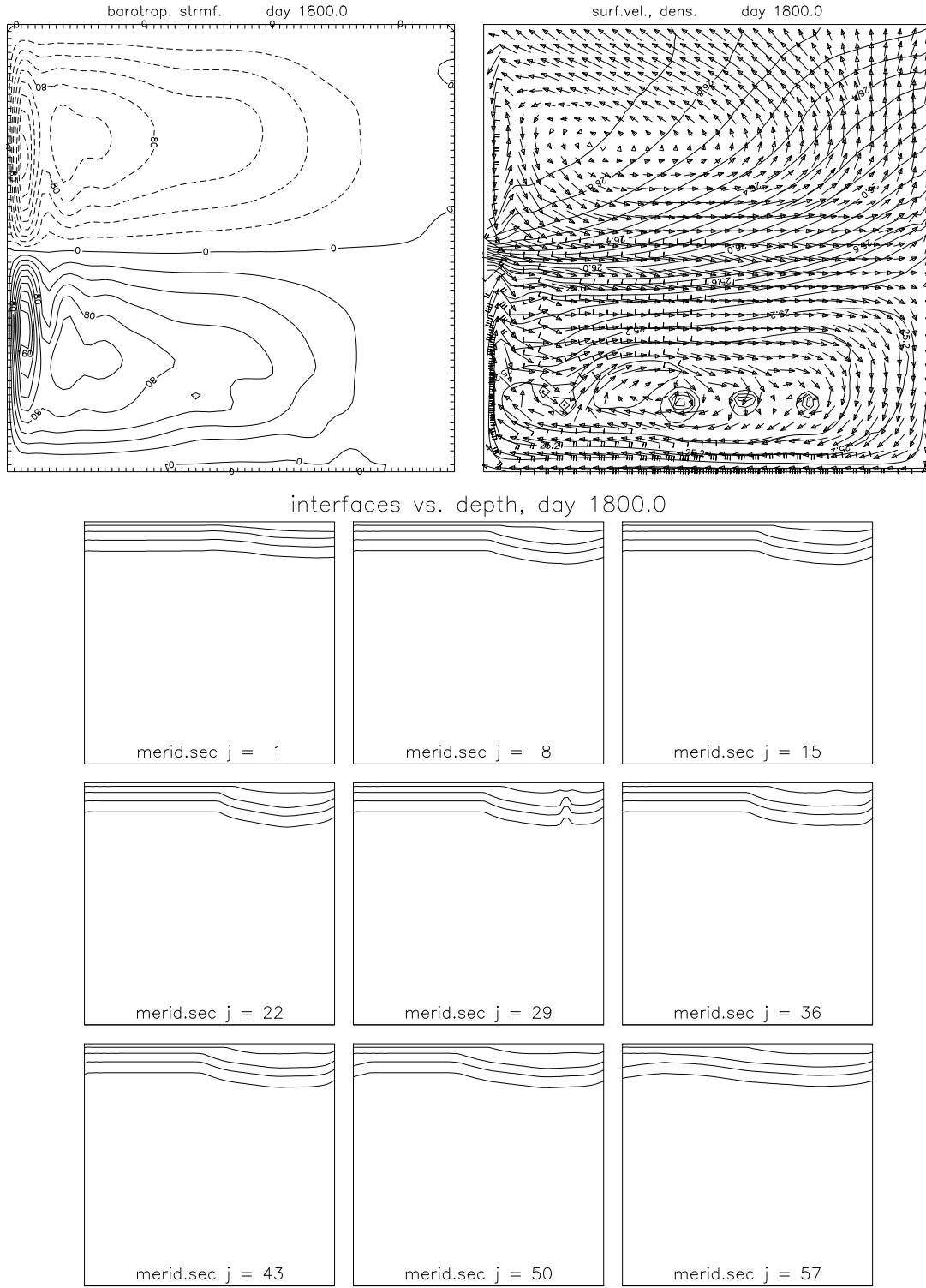


Figure 4: Results from experiment 4 at year 5.0. Upper left: barotropic stream function. Upper right: surface velocity vectors and surface density. Bottom: vertical sections through model domain along 9 equally spaced meridians progressing west to east.

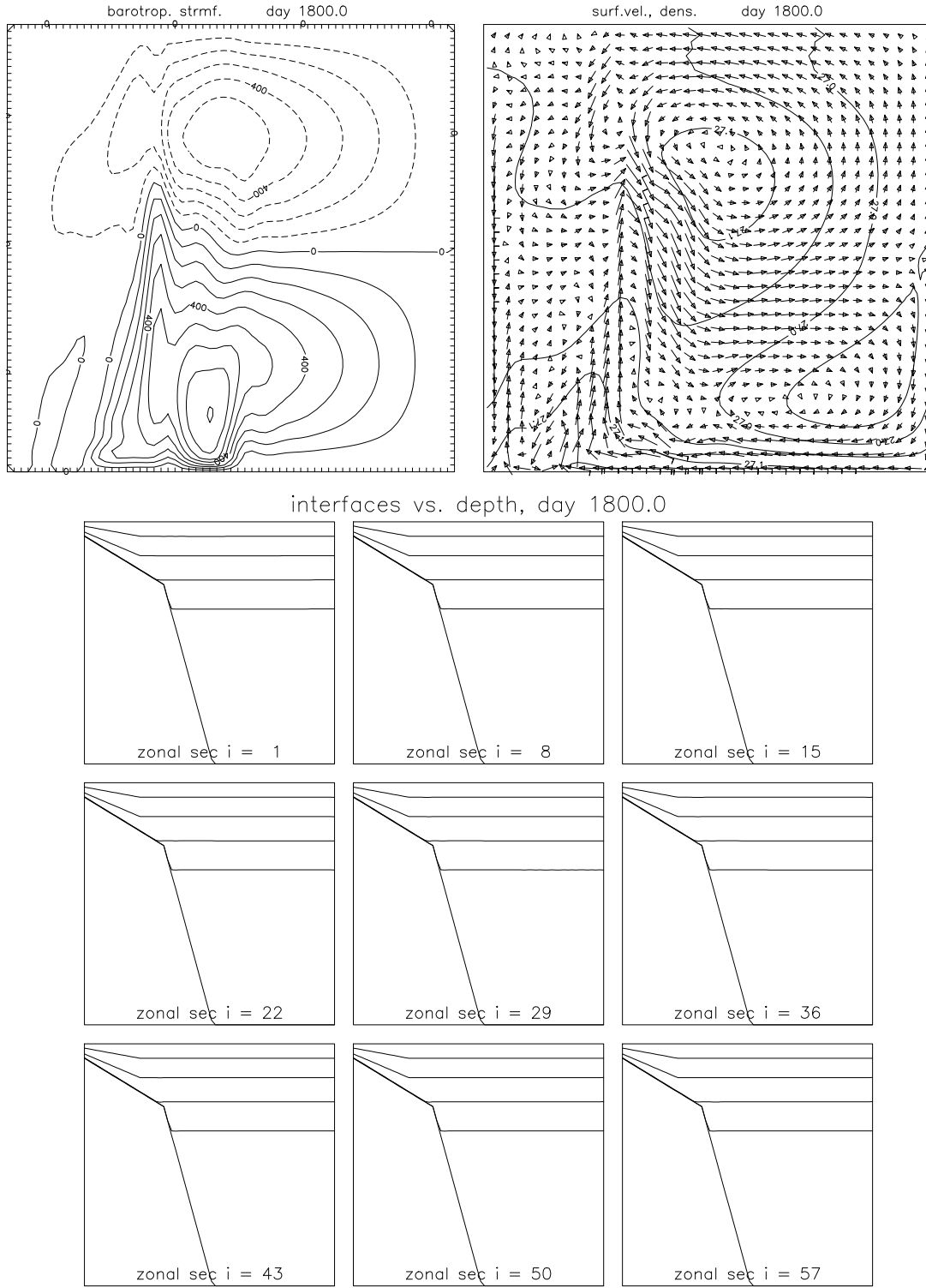


Figure 5: Results from experiment 5 at year 5.0. Upper left: barotropic stream function. Upper right: surface velocity vectors and surface density. Bottom: vertical sections through model domain along 9 equally spaced parallels progressing north to south.

The above formula can and should be tailored to particular resolution requirements or bottom depth configurations. Users wishing to use an entirely different formula can do so by locating in the routine `hybgen.F` the line where the variable `sigthk` is computed.

Results shown in Fig. 5 are based on

```
! --- minimum layer thickness (m):
thkmn(1)      = 300.
thkmn(2)      = 400.
thkmn(3)      = 500.
thkmn(4)      = 600.
thkmn(5)      = 700.
! --- initial densities (sigma_theta units):
thini(1)      = 25.6
thini(2)      = 26.7
thini(3)      = 27.4
thini(4)      = 27.8
thini(5)      = 28.0
! --- forcing choices:
airsea  = 0.          ! surface wind speed (m/s); zero -> no thermal forcing
taumax  = 0.2         ! max. wind stress (N/m^2); zero -> no wind forcing
```

The large *thkmn* values in combination with upper-ocean target values much lighter than the initial density field give the grid the appearance of a conventional compound grid combining sigma layers over the shelf with constant-depth layers in the deep ocean.

In contrast to HYCOM, HYBOX is not set up to compute horizontal pressure gradients in locations where layers impinge on a sloping sidewall and turn into massless layers. This shortcoming required the use of a nonzero *thkbot* value of 5 m in the present experiment (too small to be visible in Fig. 5).

A discussion of dynamics aspects is beyond the scope of this writeup, but an interesting feature in Fig. 5 worth mentioning is the anticyclonic vorticity maximum extending the length of the shelf break. This is a likely outgrowth of Holloway's Neptune effect.

## Concluding Remarks

The examples given above are intended as a guide for present and prospective HYCOM users interested in exploring coordinate-related parameter combinations. Such experimentation may be essential for gaining familiarity with the degrees of freedom inherent in the model's generalized coordinate framework. Some users may see in these "degrees of freedom" nothing but unwanted complexity, but others, upon detecting shortcomings of the standard coordinate layout in their particular modeling situation, may welcome the point made here that the HYCOM framework offers the opportunity to tailor the vertical coordinate (in terms of number, spacing, and definition of coordinate layers) to suit particular resolution needs.

Primary Reference: Bleck, R., An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates. *Ocean Modelling*, 4, 55-88, 2002.